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PRINCIPAL QUESTIONS OF THE THEORY OF ADAPTIVE CYBERNETIC CONTROL SYSTEMS

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Analogy of Basic Schemes of Conventional and Cybernetic Systems

Stabilization systems with constant setting date from the precybernetic period. Under "cybernetic system" we shall understand systems designed for more complicated tasks than the classical ones of stabilization, program systems or servomechanism, particularly systems with self-changing (or adaptation) of such characteristics as: a) references, b) program, c) parameters, d) law of following or nonlinearity (from type "S" to "N"), e) algorithims, f) probability, g) region of action, h) impulses, i) structure, etc.

When adaption is evaluated by one figure of merit $\underline{\underline{\Phi}}$, all systems may be realized by employing the same basic schems with only some variations. The cardinal difference lies in the principle of acting. It is possible to emloy the principle "by disturbances" or the feedback principle ("by output") (fig.1). Combined systems uniting

fig.1

both principles are the most perfect. The theory of combined systems of stabilization /4/, elaborated for conventional unadaptive systems, may with some alternations be applied to combined cybernetic systems. In this paper we consider extremum systems, which automatically find the maximum and minimum of the only figure of merit $\underline{\underline{\Phi}}$, and are the most developed examples of cybernetic systems. The reader is assumed to be familiar with four principal shemes of extremum regulators /4/.

Advantages of Combined Systems in Steady State Regimes

Energetical advantages. The output power of the feedback (or "corrector") may be taken about five times less than in systems without compound links after disturbances, the disturbances being equal. The higher the requirements of rigidity of the system, the greater the energetical advantages o the combined systems /4/.

Cybernetic advantages. The setting of the combined systems of stabilization is facilitated and extended. The real static characteristic $AA'A''$ differs from the astatic $O_2O_2'O_2''$. We can get a system having negative statism (which is necessary for the voltage drop compensation in a line) or a system having very high values of both rigidity and statism (which is necessary for parallel work of objects).

Extremum systems have a servomotor. The closest analog is a system of stabilization also possessing a servomotor. We can consider the geometrical place of the extrema in the space $L\Phi M$ as the astatic characteristic $O_2O_2'O_2''$, and the place of real work (or the hunting centre positions) as the statical characteristic $A\,A'A''$; M - is the manipulated variable; L - the main disturbance. Let us approximate the extremum characteristic by a parabola (table 1). We find the equations of statical characteristic $A\,A'A''$ (table 2), and estabilish:

1) if $l_o = 0$, $c_o = 0$, $b_1 = 0$, $n_o = 0$, we have $\Sigma_1 = -m_o\Phi$, $\frac{d\Sigma_1}{dM} = \frac{d\Phi}{dM} = 0$ and the system is identical with an astatic one and the characteristics $AA'A''$ and $O_2O_2'O_2''$ coincide.

2) Another way for changing the statical characteristic position is to make use of the compound links l_o and l_o'. Here it is possible to eliminate the statical error only in a definite "regimes without error" series /4/, where $l_o' = \beta_o$ (for conventional systems $l_o' = \frac{\beta}{\alpha_1}$) when $l_o = 0$, $b_1 = 0$.

Methods of Objective Detection of Disturbances and Manipulated Variables and Calculation of the "Optimum Compound Characteristic"

To eliminate the steady state error Δ_1 in all regimes without exception we must apply a specially selected nonlinear compound link, characteristic of which we call the "optimum compound characteristic". The method of obtaining such nonlinearity is elaborated in /5, 6/.

It is interesting to work out an objective method of detecting disturbances and manipulated variables. In the general aspect it means a method that can furnish a reply to the question: which elements are best manipulated in a system - parameters or nonlinearity, structure or codes of impulses, etc? There are no such methodd as yet. A more limited problem consists in settling which of the parameters it is best to change in order to get a more perfect extremum. Here, the optimum transient response may be found by the statistical methods of Wiener /8/ Booton and others. If difficulties are met, some rough approach may be used, correcting by experiment (appendix 1), since this gives a precise answer to the question of the choice of disturbances and manipulated variables and the existence of extremum.

Optimum characteristics have to be known only when constructing systems acting "by disturbances". When constructing feedback sysstems, it is sufficient to know whether the extremum (for example, the minimum of error) exists or not.

Servomechanisms which self change the gain dependidng on the frequency and amplitude of the sign-varied signal (fig.1) were tested experimentally. Such signals are received by accommodation systems and so-called correction servomechanisms working in combination with opened control. It has been estabilished that cybernetic systems acting "by disturbances" (fig.1 a) can work stably with a very high average gain factor, several times higher than the value obtained from the stability conditions of conventional, unadaptive systems. As soon as the frequency or the amplitude of signal decreases, the system automatically returns from the precise following regime with high gain, to the noise "smoothening" regime with low gain; the dynamic error decreasing by about 50 per cent.

Rules for Selecting Schemes of Control Systems

1) When all the noises may be measured and the amplifier characteristics are stable enough there is no necessity for using any feedback. It is sufficient to use open-cycle control "by disturbances", settled by the "conditions of invariantness".

2) When the noises cannot be measured we must use the closed system of feedback, settled by compromise setting or by statistical criteria.

3) When only a part of the noises may be measured, or when all the noises are measured but the gain characteristics are not sufficiently stable, we have to use a combined system, settled "by parts" /4/. The setting is meant to include the choice of parameter values as well as the synthesis of the scheme by employing new elements.

These rules hold for conventional unadaptive systems as well as for cybernetic extremum systems. The latter systems have easier conditions of noise measuring. It is not necessary to measure the noise itself, it is sufficient to measure some generalized parameters (for example the frequency k, noise to signal relation $\frac{a}{A}$ etc.). For periodical noise measuring, the signal can be shut off for a very short time (the method of "test impulses"); moreover in combined systems this is more frequently permissible than in uncombined /5, 6/. In the case when cybernetic control is applied to a conventional control system, we are able to consider the cybernetic regulator as secondary, supplementing the basic system for improving its operation. It may act on the feedback cycle of the basic system as well as on its open-cycle. To the secondary cybernetic regulator may be added a cybernetic regulator of the third order, adapting the characteristics of the secondary regulator, etc. Each such regulator achieves a certain step in the iterational solution of the control task (the method

of method of successive approximations). When the system actes ideally (for example, when it is settled by the conditions of invariantness) the accessory cybernetic regulator is unnecessary.

Advantages of Combined Systems in Dynamic Regimes

If, on taking into account the hunting error, the total error of the system is $\Delta = \Delta_1 + \Delta_2 + \Delta_3 + \Delta_4$, where Δ_1 is the statical error, Δ_2 the transient error, Δ_3 - the hunting error, Δ_4 - the speed error. The combined system has the following advantages in transient responses: the applicability of the invariantness conditions increases, which permits the elimination (or decrease) of statical, transient and speed errors, i.e. the increase of the speed and precision of the system. In contradistinction to the systems acting "by disturbances" only (also possessing great possibilities for satisfying these conditions), a high rigidity $S = 1 + \alpha_p$ may be attained in combined systems, which eliminates errors due to noise for which there are no compound links.

On testing the extremum regulator of the $(\frac{\text{steam}}{\text{fuel}})$ ratio, acting on the $(\frac{\text{air}}{\text{fuel}})$ relationship, developed at the Electrical Engineering Institute of the Ukrainian Academy of Sciences for steam boilers, the non-combined system was found to be impracticable (see the Ukrainian journal "Avtomatika", No. 2, 1959).

Raising of Precision and Speed by Improving Compound Links "by Disturbances"

The fundamental law for setting links "by disturbances" is satisfying the so-called invariantness conditions. Let a linear system be described by the equation $a_3(p)\varphi = b_3(p)L_1 + b_3''(p)L_2 + \dots$

where $a_3(p)$ and $b_3(p)$ are polynomials with $p = \frac{d}{dt}$ of order n and m respectively; φ is the controlled variable; L_1 and L_2 are disturbances. Then the conditions of invariantness can be written in the four forms presented in table 3.

The movements of the hunting centre of an extremum system with reference self-changing is described by linear equations with constant coefficients in derivatives or differences. For other systems (e.g.these with variable parameters) these equations are the first approach which is more precise when the departures of the centre are less. Extremal continuous test signal systems are, in essence, systems of stabilization of phase discriminator output voltage (possessing servo) at a constant value close to zero (fig.4). In systems having servo we must distinguish measuring $l(p)L$ and power (direct) $l'(p)L$ compound links. The former acts on the amplifier input, and the latter-directly on the object. In conventional systems and in extremum systems with continuous test signal for satisfying the invariantness conditions, it is possible to choose $l(p)$ and $l'(p)$. The choise of $l'(p)$ is recommended in autohunting and output sampling systems (appendix 2). To satisfy condition $(2'')$. To satisfy condition $(2'')$ it is sufficient that the optimum compound characteristic and the direct link should be linear. The other elements (e.g.servo) are not involved in the error compensation and thus it does not matter what equation they have.

The idea of complete invariantness belongs to Prof.G.V.Shcipanov /1/. The possibility of the physical realization of dynamic systems (bridge schemes) satisfying the invariantness conditions was established by Acad.V.S.Kulebakin /2/. Automatic control sydtems (distinguished by unilateral action) were shown by the author to satisfy the invariantness conditions /3/. I.R.Moore's paper /10/ belongs to this trend too. Thus, the practical value of the invariantness theory has been proved. Prof. G.V.Shcipanov's error consisted in assuming the possibility of completely eliminating error in "by output" or feedback systems, whereas in such systems it is only possible to eliminate the stable components of the error by increasing the degree of astatism (form 3a). The latter was estabilished for uniform motion and uniform

acceleration by N.Minorsky /9/. The rest of the invariantness condition forms (except 3a) may be satisfied in combined system and in systems "by disturbances" only.

The first extremum regulator acting "by disturbances" was constructed by V.A.Bogomolov and V.L.Benin at the Electrical Engineering Institute of the Ukrainian SSR Academy of Sciences /4/, and an extremum regulator with feedback was first described in /15/. The first considerable extremum system analyses were made by V.V.Kosakevich (1948) and then by Draper, Li and Lining (1951). The system of steam boiler efficiency regulator mentioned above, developed in 1958 at the Electrical Engineering Institute of the Ukrainian SSR Academy of Sciences /5/, is the first combined extremum system.

Raising Precision and Speed by Improving Feedback Loops

The fundamental law for setting the feedback loops of combined systems is the condition of "compromise setting", when the gain is chosen so that with a sufficient rigidity $\delta = 1+\alpha p$ sufficient stability (e.g. $c_{12} = 0.25$) is attained. Statistical methods of optimum transfer function selection may be applied for the same purpose. It must be kept in mind that in systems with servo the ratio ($\frac{\text{speed}}{\text{speed error}}$), called the "figure of merit", serves as rigidity measure, and the so-called "degree of stability" c_{min} /4/ serves as a stability measure. In the case when a conventional control system is used as an cybernetic control object compromise setting, or statistical methods, are employed twice: once, to the main system, and then to the cybernetic regulator itself. The peculiarity of the cybernetic regulator feedback loop synthesis consists in easy signal changing, and the feedback loop scheme and parameters are subject to small changes only, whereas in conventional systems the feedback loop scheme and parameters are varied (appendix 3).

The basic methods of weak signal reception when noises are present, employed in modern communication systems, are applicable in extremum systems as well (figs. 1, 2, 3, 4). A peculiarity is the application of correlation functions of the "relay type"

$$A'_f(\tau)=\frac{1}{T}\int_{-T} f(t)[A\,\mathrm{sign}\,f(t-\tau)]\,dt$$

$$K'_{f\psi}(\tau)=\frac{1}{T}\int_{-T}^{0} f(t)[A\,\mathrm{sign}\,\psi(t-\tau)]\,dt$$

instead of the usual proportional type /5/. This permits simpflifying the apparatus. If the rise in the noise proofing attained by the cross correlation method is taken as unity, the effect yielded by other methods, with an equal speed of system may be estimated by the following table:

- method of autocorrelation 0.8–0.9
- method of cross correlation 1.0
- method of integration (accumulation) 1.0
- methods of cross correlation and of
  signal filtration simultaneously 1.1–1.2
- method of signal complication
  ~~(digital radiolocation)~~ ....over 1.5

This order of methods holds for both open channels and when allowing for feedback. These figures have been substantiated by tests on the MH-7 model. The correlator eliminates disturbances on the same principle as the synchrodetector. The advantages of the signal complication method are accounted for by the fact that it increases the quantity of information; a complicated signal being more readily distinguished from interference than a simple one. An example of a system giving K and I letter signals (in Morse code) is shown in fig.4. Since the signal complication method has not been worked out as yet, and the integration (accumulation) method is rather complicated, the cross correlation method is best for practical purposes /fig.28/. The basic apparatus necessary for effecting this method is now being

produced serially (e.g. BTИ regulator of the ЭР -type) /5/. Extremum control systems, constructed on the basis on this universal regulator, will differ from one another only by the measuring element, producting d.c. voltage proportional to the "figure of merit" (of the extremum) φ.

Orthogonality (Non-correlation) of Two Setting Methods

When the conditions obtained below 1) $\lambda \neq f(\varphi)$, i.e. $Z(p)=0$

ore 2) $b_3(p)=\beta(p)+\ell'(p)+Y_1(p)Y_2(p)\frac{1}{p}\ell(p)=0$

are satisfied, the methods of increasing precision and speed by improving disturbance links are connected with the choice of coefficients of the right side of the system dynamics equations; and the methods of improving closed loops, with the choice of coefficients of the left side (fig.5, showing this, is taken from /3/. The effect of compound links on the stability is not great. The setting of both basic and secondary (cybernetic) combined systems may be effected by the "by parts" method: first, maximum improvement of the closed feedback loop, and then second, of the open compound links by disturbances and noises.

Appendixes and Tables

Appendix 1. Example of Method of Choosing Input Variables.

A servosystem which is to be the object of cybernetic control is described by equations of dynamics

$$\Sigma = S - \Phi - m_1 p \Phi$$

$$M = \alpha_1 \Sigma$$

$$(T_1 p + 1) p \Phi$$

The system is acted upon simultaneosly by signal and noise: $S(t)=\psi(t)+N(t)$. Applying the rough approach method of G.Dutile /8/, we find that the minimum error is attained when the spectral densities of signal and interference are equal: $S_\psi(\omega_c)=S_N(\omega_c)$ where $\omega=\omega_c$ is the cut (or limit) frequency of the closed system. $S_\psi(\omega)=\frac{A^2}{\pi}\cdot\frac{2K}{(2K)^2+\omega^2}$

is the sign-varied square signal

$S_N(\omega) = a^2$ is the white noise.

As the second design equation is an expression (or plotted function) for the cut frequency, obtained from the above equations of the system elements

$$\omega_c = f_1(C_{12}, \omega_0), \text{ where } C_{12} = \frac{1+\alpha_p m_1}{2\omega_0 \tau};\ \omega_0 = \sqrt{\frac{\alpha_p}{\tau}};\ \alpha_p = \alpha_1 \alpha_2 \qquad (2)$$

Solving (1) and (2) graphically we find the monogram /5, 6/:

$$f_2\left(\frac{A}{a}, K, C_{12}, \omega_0\right)$$

This monogram answers the following questions:

1. What variables are to be considered as disturbances ($\frac{A}{a}$ and k)?
2. What parameters are to be manipulated (c_{12} and ω_0)?

Thus, the rough approach gives exact answers to the principal questions. The monogram also makes it possible to determine approximately the "optimum compound characteristics" $C_{12} = \ell_0'\left(\frac{A}{a}, K\right)$ and $\omega_0 = \ell_0''\left(\frac{A}{a}, K\right)$. These characteristics may be made more precise by experiment afterwards.

Appendix 2. Choice of Compound Links Coefficients by Invariantness Conditions

For the system of stabilization described by equations:

control law: $\Sigma = \Psi - m(p)\Phi - \ell(p)L$

amplifier and servo: $M = Y_1(p)\frac{1}{p}\Sigma$

object: $\Phi = A + Y_2(p)M - \beta(p)L + \ell'(p)L$

load (controlled system): $\frac{\Phi}{L} = Z(p)$

we obtain the following characteristical equation (for the variable Φ): $1 + Y_1(p)Y_2(p)m(p) + \dfrac{\beta(p) + \ell'(p) + Y_1(p)Y_2(p)\frac{1}{p}\ell(p)}{Z(p)} = 0$

Second form of the invariantness conditions:

$$\beta(p) + \ell'(p) + Y_1(p)Y_2(p)\frac{1}{p}\ell(p) = 0$$

Whence

when $\ell'(p) = 0$ $\quad \beta(p) + Y_1(p)Y_2(p)\frac{1}{p}\ell(p) = 0 \qquad (2')$

when $\ell(p) = 0$ $\quad \beta(p) + \ell'(p) = 0 \qquad (2'')$

We determine: 1. Conditions 2' and 2" may be realized only in systems where the choice of l(p) or l'(p) is possible, i.e. in combined systems and in systems acting by disturbances.

2. Compound links l(p) and l'(p) may be considered as opened and fail to affect the stability only in case of the invariantness conditions being satisfied or when $Z(p) = \infty$. In /4/ the case is considered when $Z(p) = \lambda_0 + c\Phi$, and error overcompensation is found to result in hunting (auto-oscillations).

For an extremum system with continuous test signal the following equations hold:

control law: $\Sigma = -\Theta + \ell(p)L$

amplifier: $U = Y_4(p)\Sigma$

servo: $M = Y_1(p)\frac{1}{p}U$

Linear part of object: $M_1 = Y_2(p)[M + \ell'(p)L]$

nonlinear part of object: $(\Phi + \Phi_0) = -a(M_1 - \Sigma_{20})^2$

phase discriminator (correlator): $\Theta = Y_3(p)[M_1 - \Sigma_{20}]$

where $\Phi_0 = b_0 + b_1 L$, $\Sigma = C_0 + \beta L$

For variables Σ, Θ, U, M and M_1, there is a closed system of linear equations. Let for instance $Y_0(p) = Y_1 Y_2 Y_3 Y_4$; $\frac{1}{Y_0(p)} = \tau p + 1$, $\ell'(p) = 0$, $C_0 = 0$ Then we obtain: $(p^2 + a_1 p + a_2)\Theta = (b_0 p^2 + b_1 p + b_2)L$

Let us take nondimensional timing: $\omega_0 = \sqrt{a_2}$; $T = \omega_0 t$; $D = \frac{d}{dT}$

$(D^2 + 2C_{12}D + 1)\vartheta = (\gamma_2 D^2 + \gamma_1 D + 1)L$ where $C_{12} = \frac{1}{2\sqrt{\tau a}}$

Solution: 1) when $L = [1]$: $\Theta = \gamma_0 - e^{-C_{12}T}(a\cos\beta_{12}T + b\sin\beta_{12}T)$;

where $a = \gamma_0 - \gamma_2$, $b = \frac{\gamma_0 C_{12} - \gamma_1 + \gamma_2 C_{12}}{\beta_{12}}$ and $\beta_{12} = \sqrt{1 - C_{12}^2}$

2) when $L = vt$: $\Theta = \gamma_0 T - \Delta_4 + e^{-C_{12}T}(a\cos\beta_{12}T + b\sin\beta_{12}T)$

where $a_1 = \Delta_4 = 2C_{12}\gamma_0 - \gamma_1$; $b = \frac{2C_{12}^2\gamma_0 - C_{12}\gamma_1 + \gamma_2 - \gamma_0}{\beta_{12}}$

Invariantness conditions: $\gamma_2 = \gamma_0$ and $\gamma_1 = 2C_{12}\gamma_0$

Transient response forms, with $\Delta_4 = 0$, are shown in figure 5.

This example shows the selection of measuring link coefficients l(p).

Let us also consider the choosing of direct link coefficients l'(p).

It is necessary to distinguish two cases:

1. The object consists of inertial and nonlinear parts. The optimum compound characteristic is known:

$$M_1 = Y_2(p)[M + \ell'(p)L] \qquad \text{and} \qquad M_1 = \xi_1 L$$

Then in order that when is varied, servo should not be switched on, it is necessary that:

$$M_0 = 0, \quad \ell'(p) = \frac{\xi_1}{Y_2(p)} = \ell'^{\circ} + \ell'_1 p + \ell'_2 p^2 + \dots + \ell'_n p^n$$

2. In an object equivalent circuit, the nonlinear part is placed first, and then the inertial. In this case for a continuous test sig-system we obtain.

control law: $\Sigma = -\Theta + \ell(p)L$

amplifier: $U = Y_4(p)\Sigma$

servo: $M = Y_1(p)\frac{1}{p}U$

nonlinear part of object: $(M_1 - M_0) = -a(M - \Sigma_{10})^2$

linear part of object: $\Phi = Y_2(p)M_1$

phase discriminator (correlator): $V = Y_3(p)M_1$

where $M_{10} = b_0 - b_1 L$; $\Sigma_{10} = C_0 + \beta_0 L - \ell'_0 L$ or $\Sigma_{10} = C_0 + \beta_0(L) + \ell'_0(L)$

In this case for complete invariantness, it is sufficient to use compound follow-up link, chosen in accordance with the optimum compound characteristic (when l(p)=0).

For a linear system: $\Sigma_{10} = C_0 + \beta_0 L - \ell'_0 L = \text{const.}$ or $\beta_0 = \ell'_0$

for a nonlinear system: $\Sigma_{10} = C_0 + \beta_0 L - \ell'_0(L) = \text{const.}$ or $\beta_0(L) = \ell'(L)$

In /5, 6/ a method is developed for choosing direct compound link nonlinearity, and the approximate replacement of the by several disturbances link $\ell'_0(L_1 L_2 L_3 \dots L_n)$ by a simpler sum of links: $\ell'_{01}(L_1) + \ell'_{02}(L_2) + \ell'_{03}(L_3) + \dots + \ell'_{0n}(L_n)$ is discussed.

Appendix 3. Example of Applying the Statistical Method

Let the extremum regulator with forced hunting (i.e. with modulation or output sampling) change the manipulated variable M by the square iipulses law. The autocorrelating function of such a signal is $A_M(\tau) = A^2 e^{-2K\tau}$ where k is the frequency. This variable together with interference of "white noise" type, for which $A_N(\tau) = a^2$, passes through a circuit (consisting of an object and measuring elements) the impulse function of which is known, e.g. $W(t) = We^{-\frac{t}{\tau}}$ (first order object). For better noise-proofing of the system it is necessary, that the interference to signal ratio on the measuring element input should be as small as possible. Using

Wiener's formula in a form obtained in Jones' paper /8/ we find:

$$W(t) \leqslant A_\mu(t) \quad \text{or} \quad W \leqslant A^2 \quad \text{and} \quad K \leqslant \frac{1}{2\tau}$$

The practical conclusion from this example consists in the choice of the optimum number of switchings-in of the servo per unit of time $K \leqslant \frac{1}{2\tau}$

TABLE 1

	Equations for steady-state regimes For stabilization systems	 For extremum system
law of regulation	$\Sigma_1 = -m_0\Phi - n_0M + \ell_0L + k\Psi$	$\Sigma_1 = -m_0\Phi - n_0M + \ell_0L$
regulator with proportional speed	$pM = \alpha_3\Sigma_1 = 0$	$\frac{d\Sigma_1}{dM} = 0$
Object of regulation	$\Phi = \alpha_1\Sigma_2 - \beta L$ where: $\Sigma_2 = M + \ell_0'L$	$\Phi - \Phi_0 = -a(\Sigma_{20} - \Sigma_{21})^2$ where: $\Phi_0 = b_0 + b_1L$ $\Sigma_{20} = c_0 + \beta L$; $\Sigma_{21} = M + \ell_0'L$

TABLE 2

Statical characteristics	Stabilization system	Extremum system
In plane M–L	$M = \xi_0 + \xi_1 L_1$ where: $\xi_0 = \frac{K_0}{\alpha_1 m_0 + n_0}\Psi$ $\xi_1 = \frac{m_0(\beta - \alpha_1\ell_0') + \ell_0}{\alpha_1 m_0 + n_0}$	$M = \xi_0 + \xi_1 L$ where: $\xi_0 = c_0 + \frac{n_0}{2am_0}$ $\xi_1 = \beta - \ell_0'$
In plane Φ – M	$\Phi = \sigma_0 - \sigma_1 M$ where: $\sigma = \frac{K_0(\beta - \alpha_1\ell_0')}{m_0(\beta - \alpha_1\ell_0') - \ell_0}\Psi$ $\sigma_1 = \frac{n_0(\beta - \alpha_1\ell_0') - \alpha_1\ell_0}{m_0(\beta - \alpha_1\ell_0') - \ell_0}$	$\Phi = \sigma_0 - \sigma_1 M$ where: $\sigma_0 = \frac{b_0\xi_1^2 - b_1\xi_0\xi_1 - a[c_0\xi_1 - \xi_0(\beta - \ell_0')]^2}{\xi}$ $\sigma_1 = \frac{b_1\xi_1 + 2a(\xi_1 - \beta + \ell_0')[c_0\xi_1 - \xi_0(\beta - \ell_0')]}{\xi_1^2}$
In plane Φ – L	$\Phi = \gamma_0 + \gamma_1 L$ where $\gamma_0 = \frac{\alpha_1 K_0}{\alpha_1 m_0 + n_0}\Psi$ $\gamma_1 = \frac{n_0(\beta - \alpha_1\ell_0') - \alpha_1\ell}{\alpha_1 m_0 + n_0}$	$\Phi = \gamma_0 + \gamma_1 L$ where $\gamma_0 = b_0 - a(\xi_0 - c_0)^2$ $\gamma_1 = b_1 - 2a(\xi_1 + \ell_0' - \beta)(\xi - c_0)$

TABLE 3

No.	Forms of invariantness conditions	Forms in which the disturbances have to be given	Part of error eliminated	Means of realization
1	$L_1(t)=0, L_2(t)=0$ (1)	of no practical importance		
2	$b_3(p)=0$ $b_3''(p)=0$ (2)	in any form (for nonlinear systems - with a limit by acceleration /4/)	total error caused by disturbances L_1 and L_2	control by disturbances and their time derivatives
3	$\frac{b_3(p)}{a_3(p)} \cdot L(t)=0$ (3); $\frac{1}{a_3(p)} \cdot L_1(t)=0$ (3a)	in the common form, in letters	steady-state component only, caused by <u>all</u> disturbances	integral control /9/
	$b_3(p) \cdot L_1(t)=0$ (3б)	The same	steady-state component only, caused by <u>one</u> disturbance L_1	control by disturbances and their time derivatives
4	$b_3(p)L_1(t)+ b_3''(p)L_2(t)= =0$ (4)	in numerical form	total error caused by disturbance L_1	displacement device $L_2(t)$ (forcing device) and artificial changing of reference in the program systems (see /4/p.293).

The conditions are real for the linear systems - a) with zero initial conditions of transient response b) when n m

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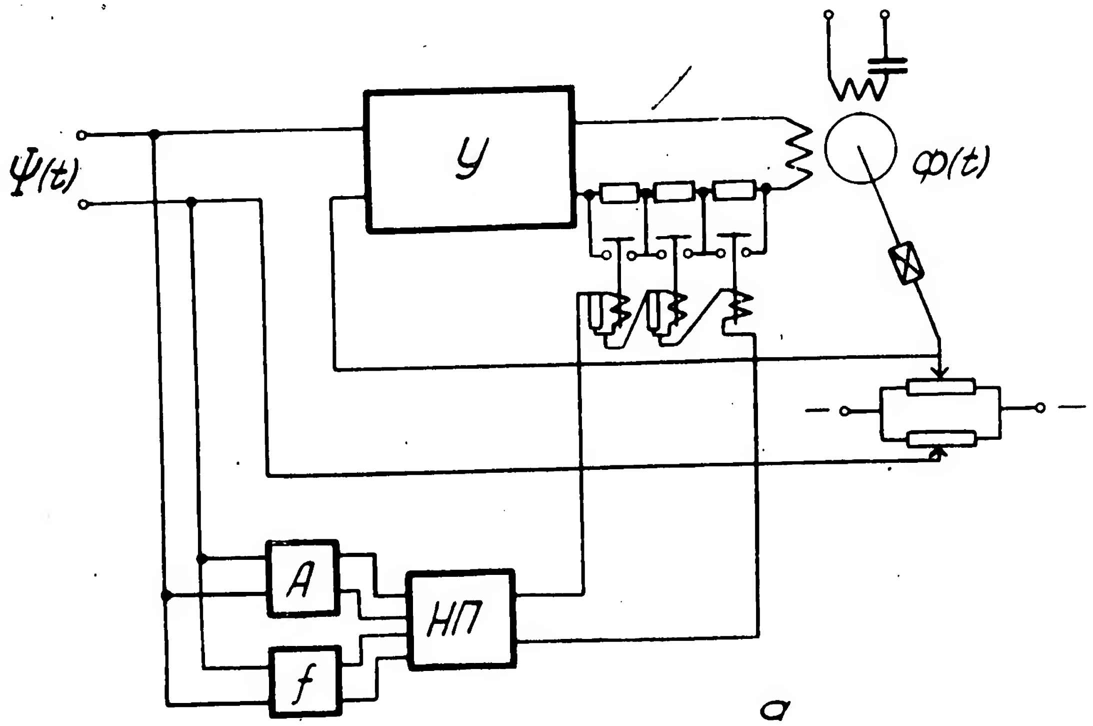


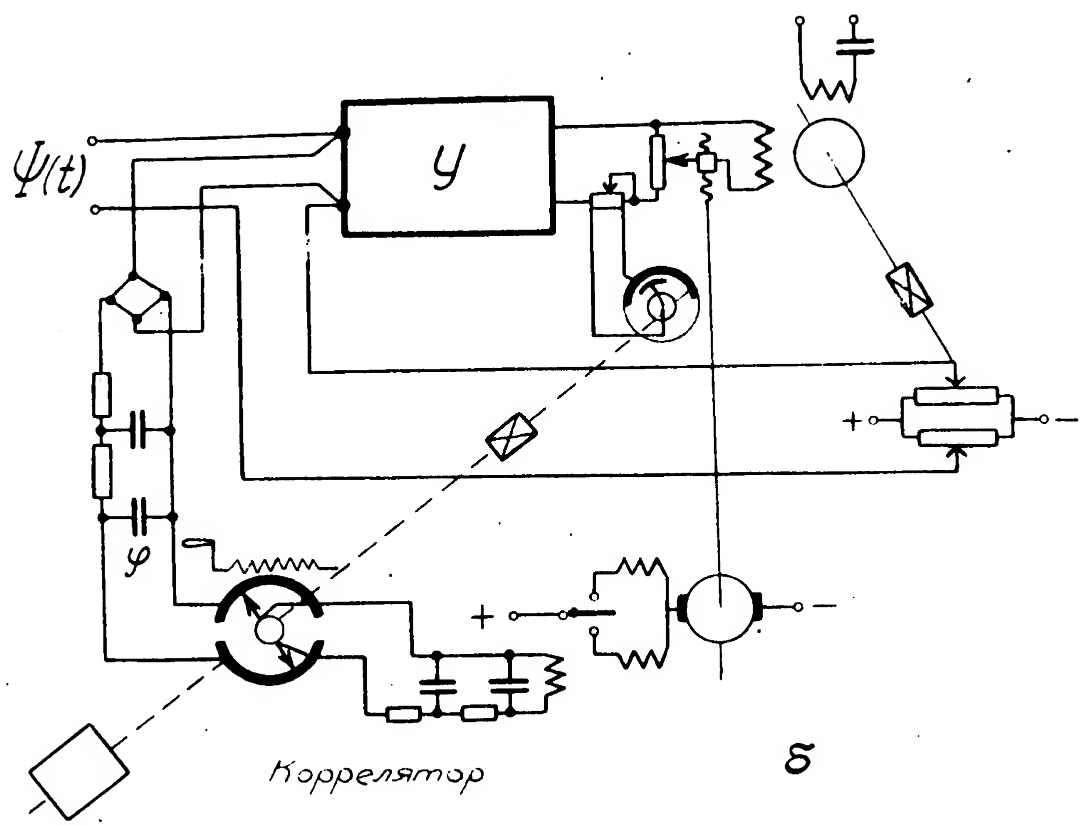


Рис. 1. Примеры приспособливающихся следящих систем с самоизменением коэффициента усиления:
а) по принципу „по возмущениям",
б) по принципу „по отклонению" (или обратной связи).
У - усилитель, А - измеритель амплитуды, f - измеритель частоты, НП - нелинейный преобразователь

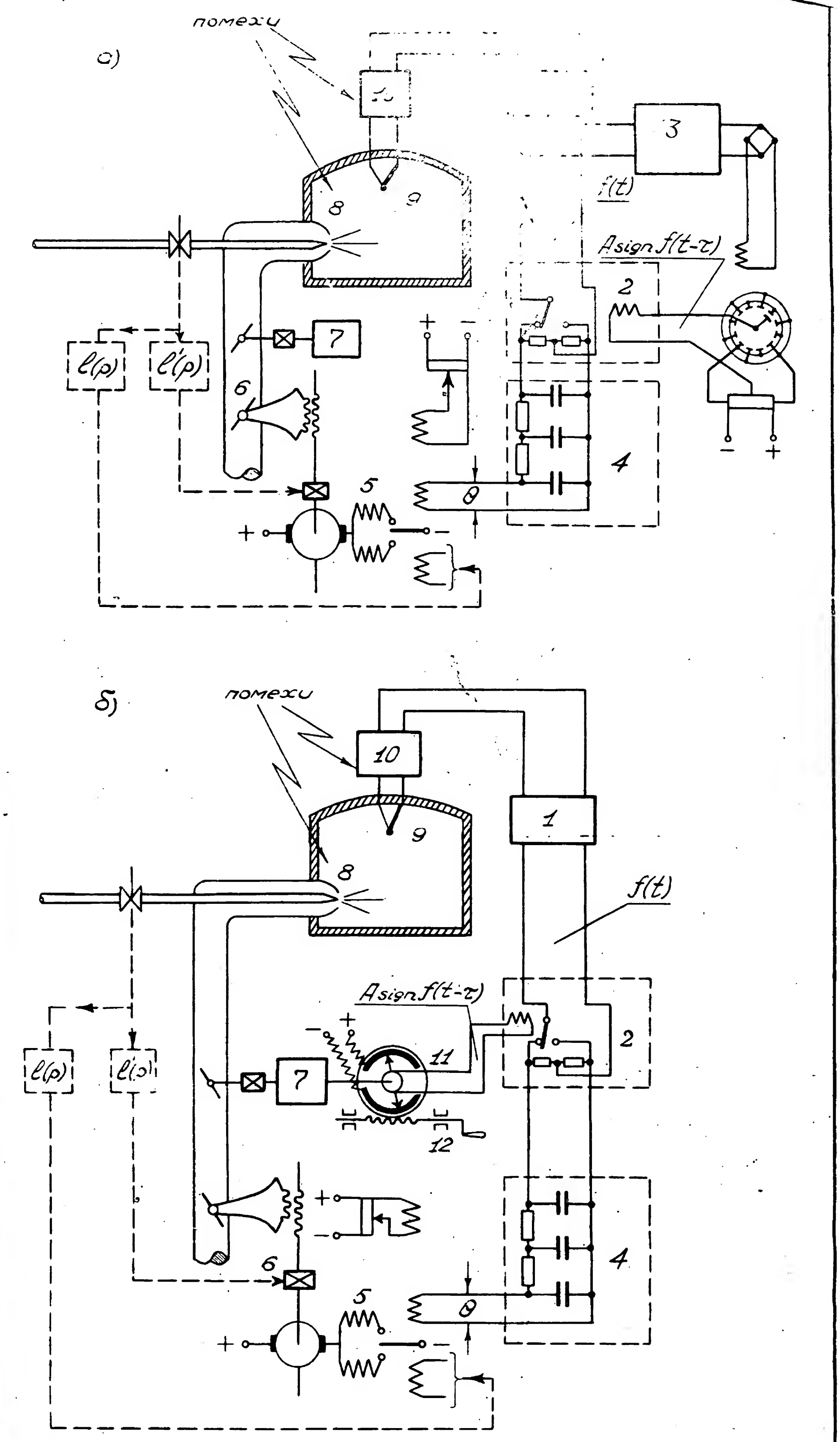


Рис.2. Схемы корреляционных экстремальных регуляторов температуры: а) автокорреляционный; б) взаимнокорреляционный.

1-усилитель, 2-релейный умножитель, 3-линия задержки, выпрямитель и генератор опорного напряжения, 4-сглаживающий фильтр, 5-сервомотор, 6-исполнительный орган, 7-модулятор подачи воздуха, 8-форсунка, 9-термопара, 10-усилитель.

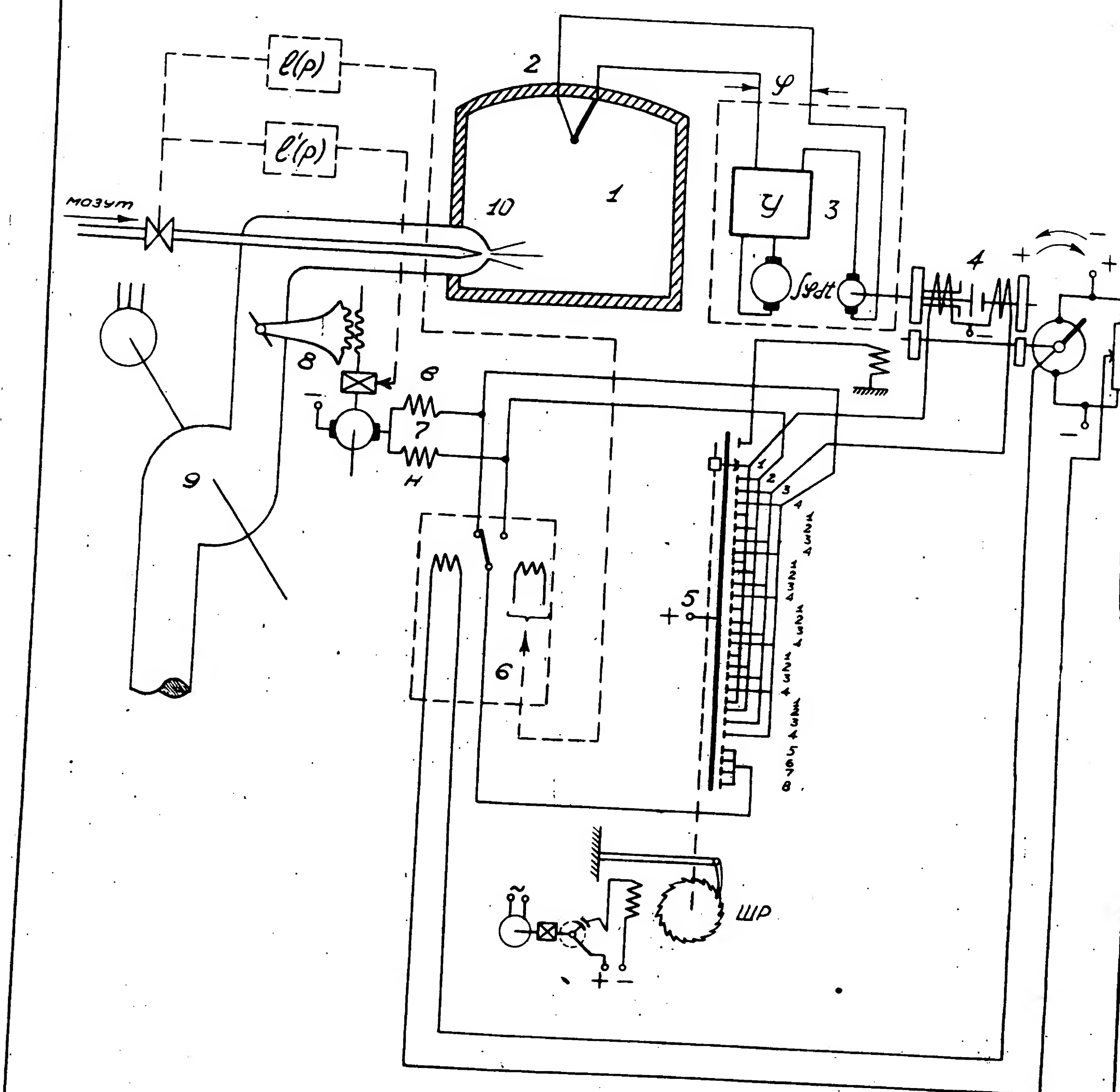


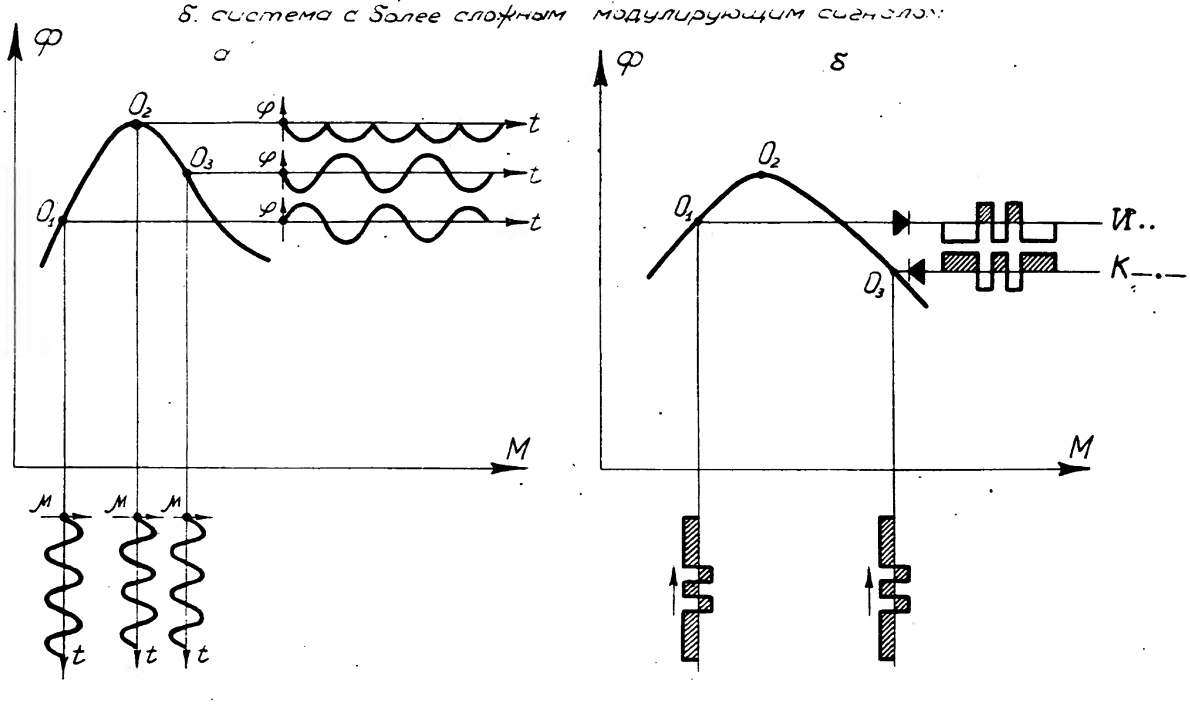
Рис. 3. Схема экстремального регулятора с интегрированием по способу „чересполосицы."

1-топка, 2-термопара, 3-интегратор, 4-реверсивная муфта, 5-шаговый распределитель, 6-реле, 8-сервомотор, 9-вентилятор, 10-форсунка, 7-реверсирующие обмотки.

Рис.4. Пример осуществления метода усложнения модулирующего сигнала

а. система с гармонической модуляцией

б. система с более сложным модулирующим сигналом



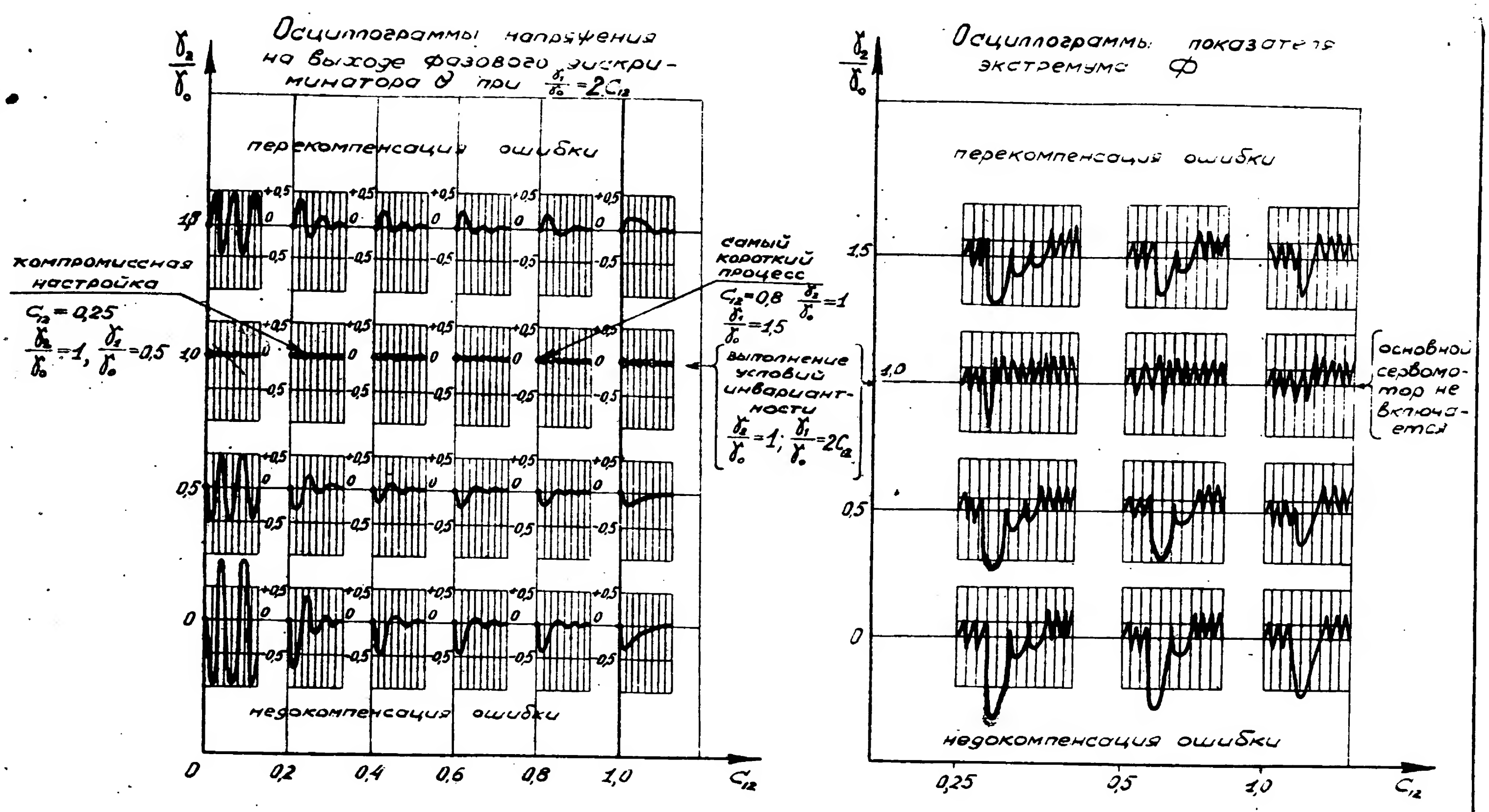


Рис. 5. Влияние связи по возмущению (координата $\frac{\gamma_2}{\gamma_0}$) и затухания (координата C_{12}) на форму переходных процессов в комбинированной системе с уравнением $(D^2+2C_{12}D+1)\theta=(\gamma_2 D^2+\gamma_1 D+\gamma_0)L$